Plasma-Facing Material Development Strategy in ITER

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with collaboration with International Tokamak Physics Activities, EU PWI TF, USBPO….

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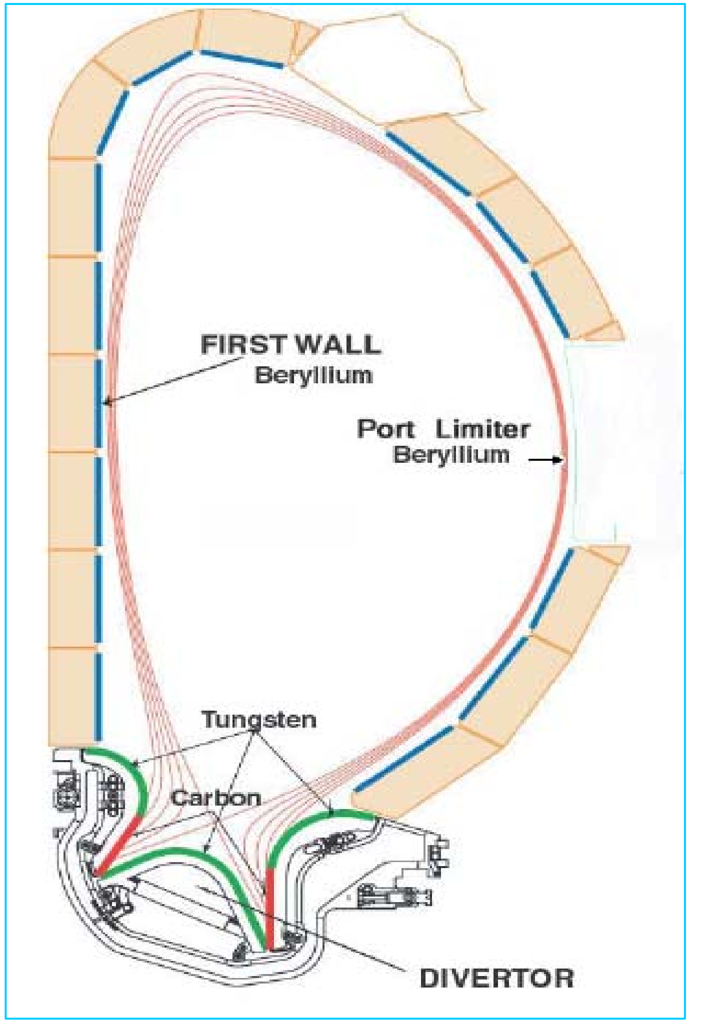
Introduction
- Challenges for ITER

- Plasma stored energy ~ 350 MJ (present tokamaks <10 MJ)
- Long pulse (~400 s burn) and steady state (~3000 s)
- Nuclear
  - Tritium inventory < 700 g
  - Dust < 1 tonne in VV

Plasma Facing Material Choice

- In the initial operation ITER uses beryllium FW, tungsten divertor baffle and dome, and carbon target plates to maximize the operation flexibility
- During H and D phases, configuration with separatrix shifted upwards would allow preliminary assessment of tungsten divertor with modest plasma performance
- Before DT operation, the divertor target will be changed to tungsten to minimize the tritium retention, but the option of limited use of CFC during DT is not ruled out
- Scenarios with Be/W PFC must be developed



Heat load specifications

- Heat load specifications of PFCs have been revised to reflect recent experimental results [Loarte, IAEA ’08]
- New specifications cover the steady-state heat loads as well as transient heat loads e.g. disruptions, VDEs and ELMs
- These specifications confirm very serious consequences of ELMs, disruptions and VDEs on PFCs, indicating the need of mitigating or avoiding these phenomena
- These specifications have large uncertainty, requiring continued experiments in the existing tokamaks

Lifetime of PFCs

Unmitigated ELM:~10 MJ/m^2

ELM induced erosion

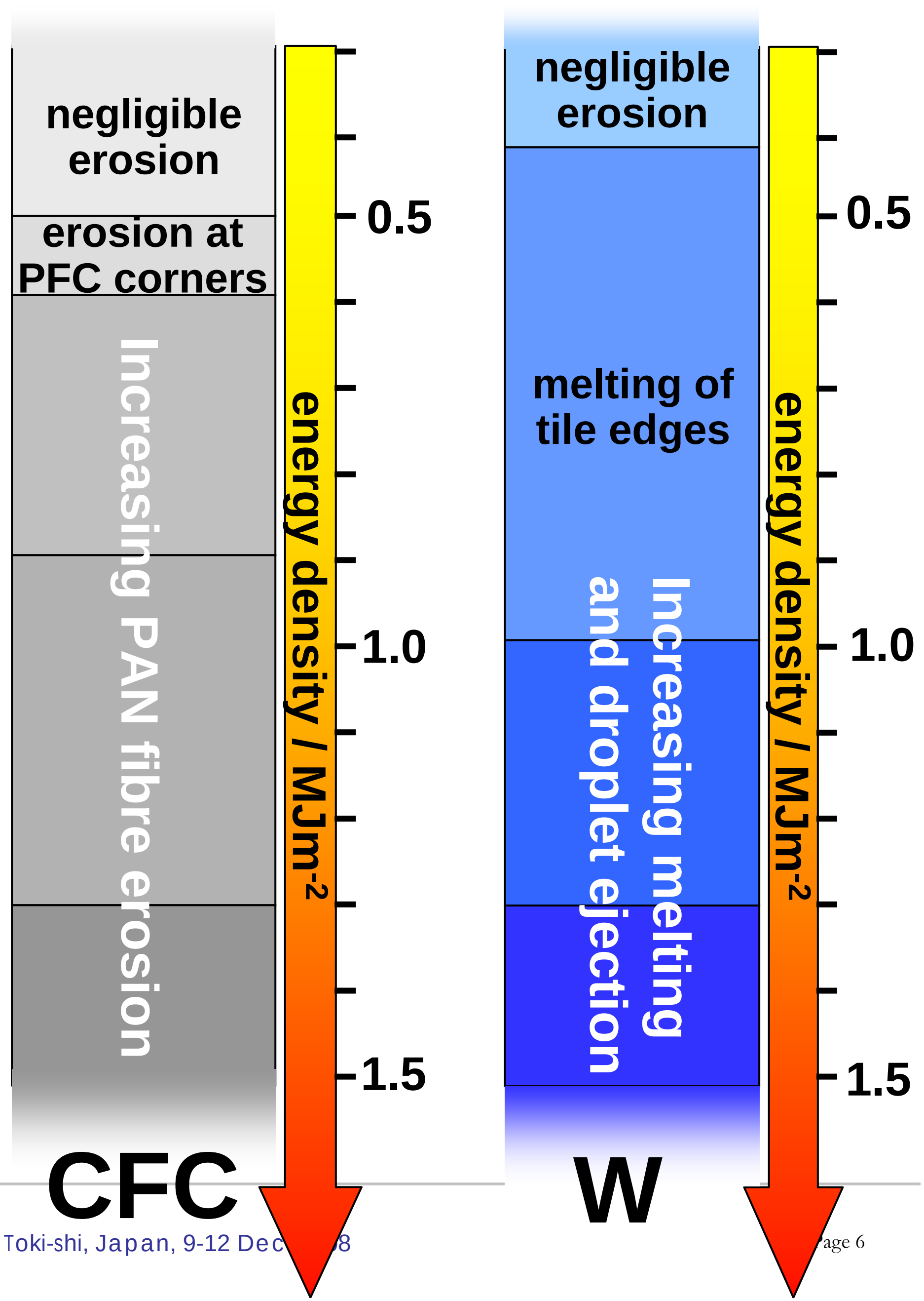
Results from Russian plasma simulators:

- ❑ Erosion limit for CFC reached due to PAN fibre erosion
- ❑ Erosion limit for W reached due to melting of tile edges

Crack formation was observed at energy densities ⩾ 0.7 MJ/m^2. Repetitive sub-threshold ELM investigations ongoing in JUDITH2

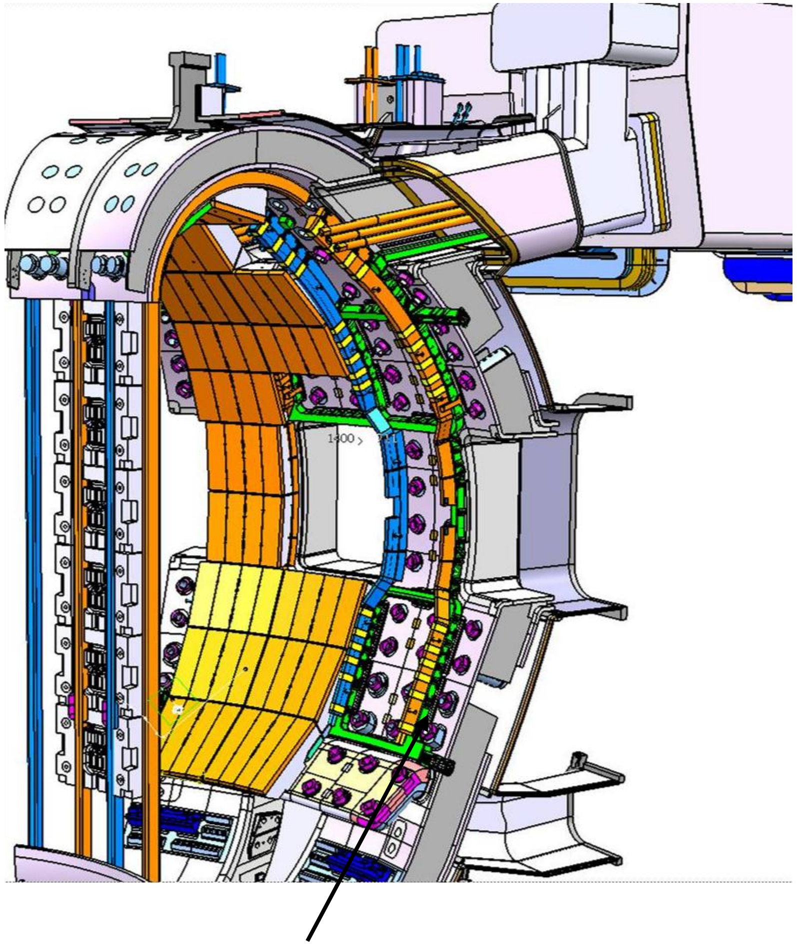
Recommended threshold for damage 0.5 MJm^{-2}

Efficient mitigation methods (factor of 20) needed



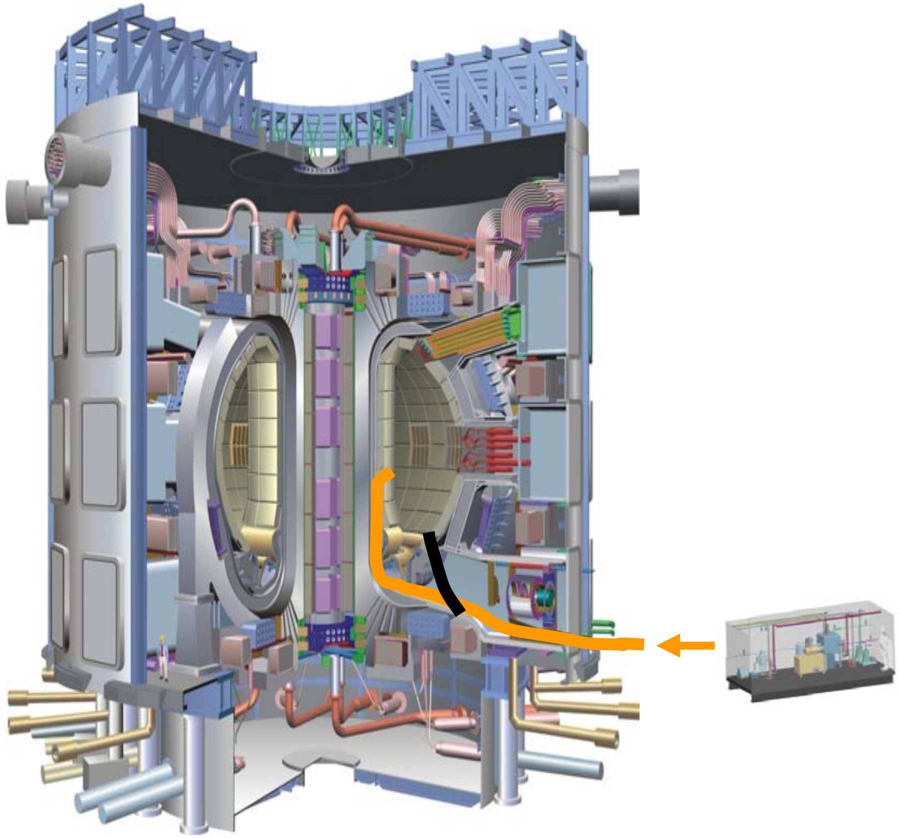
ELM mitigation

In-vessel coils



ELM coils

pellet injection



Requirement of mitigation – target values

Energy load on divertor plate due to Disruptions

Erosion of divertor plate during Thermal Quench

- **Stored energy:** W = (120–175) MJ for reference ELMy H-mode discharge,
- **In:Out asymmetry:**
  2:1 $\Rightarrow$ E_{in} = (80-117) MJ (inner), E_{out} = (40-58) MJ (outer),
  1:1 $\Rightarrow$ E_{in} = (60-88) MJ (inner), E_{out} = (60-88) MJ (outer),
- **Expansion of wetted area of divertor : 5-10**
  inner target plate S = (5-10)$\times S_{in} \approx$ (5-10)$\times$1.3m^2 = (6.5-13) m^2,
  outer target plate S = (5-10)$\times S_{out} \approx$ (5-10)$\times$1.7m^2 = (8.5-17) m^2,
- **Energy deposition rise time :** τ = (1.5-3) ms,

Most severe case (inner plate):

E_{in}=117 MJ, S=6.5 m^2, τ=1.5 ms

$\varepsilon \equiv f_T^{-1} E_{in}/(S \cdot \tau^{0.5}) \approx 388\ \mathrm{MJ/m^2/s^{0.5}}$:

where f_T is a factor for temporal shape of energy input (≈1.2)

Critical value for melting of tungsten (triangular wave) ε_{melt}

$\varepsilon_{melt} \approx 48\ \mathrm{MJ/m^2/s^{0.5}}$.

Energy flux due to disruptions needs to be reduced by

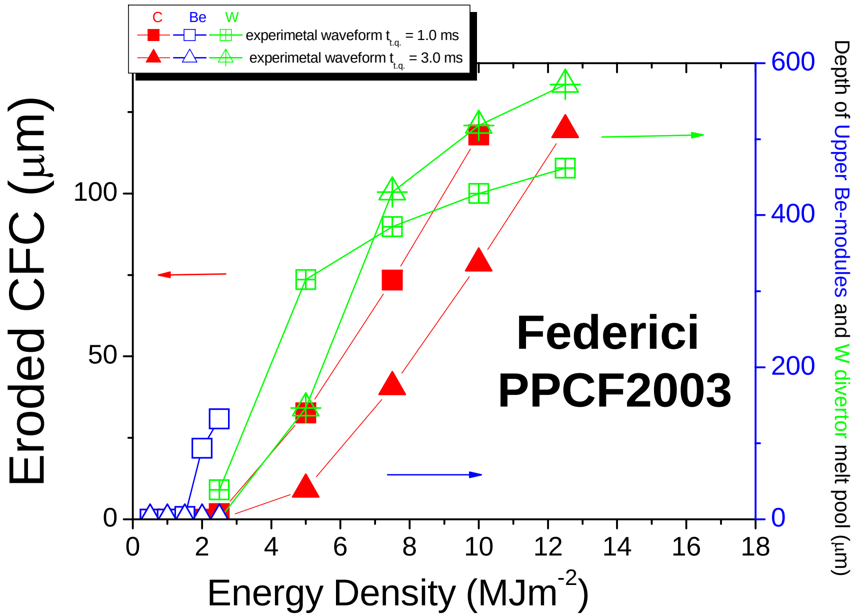
$\varepsilon / \varepsilon_{melt} \approx 388 / 48 \approx 8$,

⇒ Target value of mitigation ≈10

Case	Inner/Outer	Energy density (MJ/m^2)	ε	$\varepsilon / \varepsilon_{melt}$
Most severe	Inner	18	388	8
	Outer	10.4	223	4.6
Mildest	Inner	4.6	70	1.5
	Outer	2.4	43	0.9

Without mitigation (if entire melt layer is lost)

- **Worst case; 10-18 MJ/m^2 ⇒ 0.5mm ≤ melt layer**
- **Mildest case; 4.6-2.4 MJ/m^2 ⇒ 0.1-0.3 mm ≤ melt layer**



⇒ Lifetime of target plate :

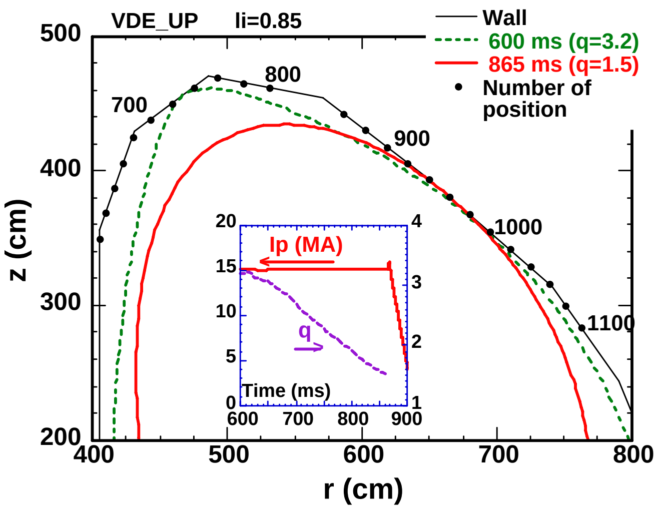
≈ 20 disruptions (worst case)

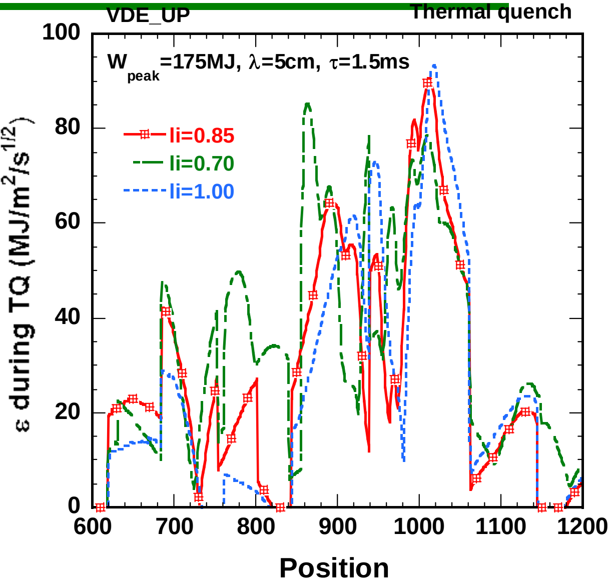
≈ 30-100 disruptions (mildest case)

M. Sugihara

VDEs (upper Be wall)

Estimation by Ideal contact with wall





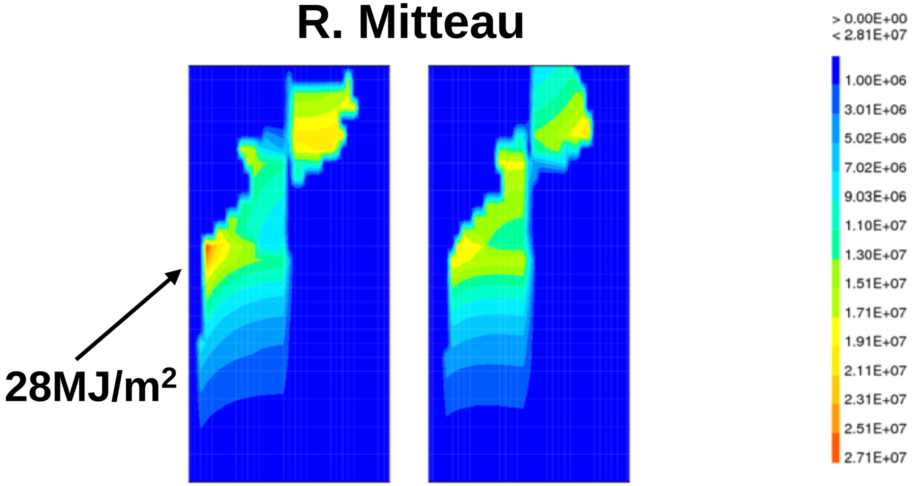
Most severe case
270 MJ, λ_p=3cm
ε =230 MJ/m^2/s$^{0.5}$

For Be wall:
230/25≈9

Target value
≈10

Shaped wall (not yet optimized yet)

R. Mitteau



28 MJ/m^2
⇒ ε =700 MJ/m^2/s$^{0.5}$
⇒ ≈ 30 mitigation needed

Further shape optimization is on-going

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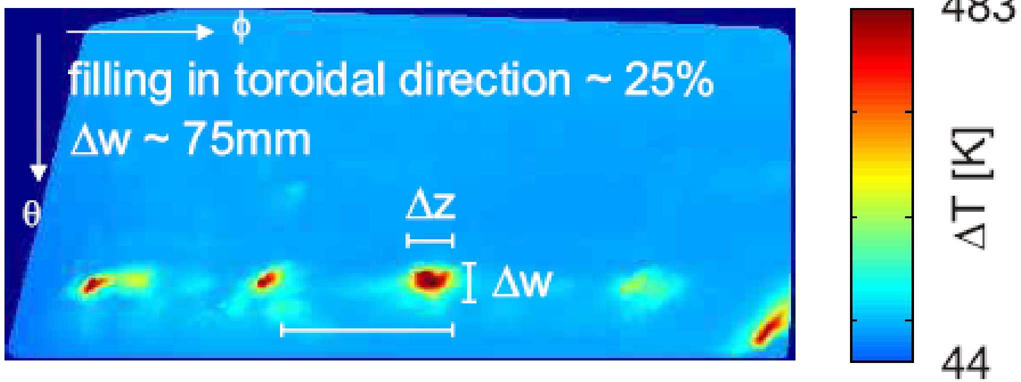
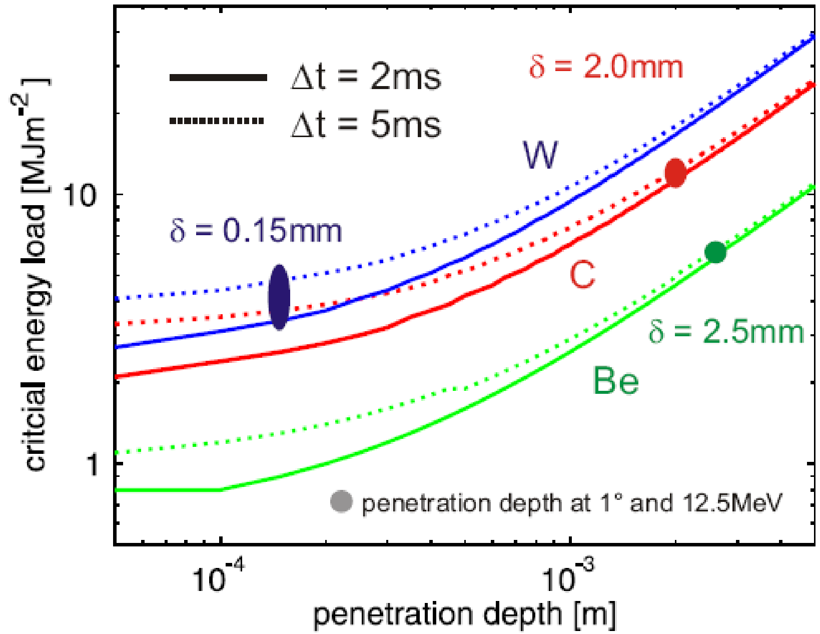
Runaway Electrons

Simple extrapolation from JET





Wetted area ≈ 0.3 m² in JET

⇒

Wetted area ≈ (0.3-0.6) m² ITER

Beam energy in ITER ≈ 20 MJ

⇒

Energy density ≈ (35-70) MJ/m²

Penetration depth (12MeV) 2.5-7.5 mm (1°- 3°)

⇒ $E_{critical}$ ≈ 6-14 MJ/m²

Required mitigation (35-70)/(6-14) ≈ 2.5-12

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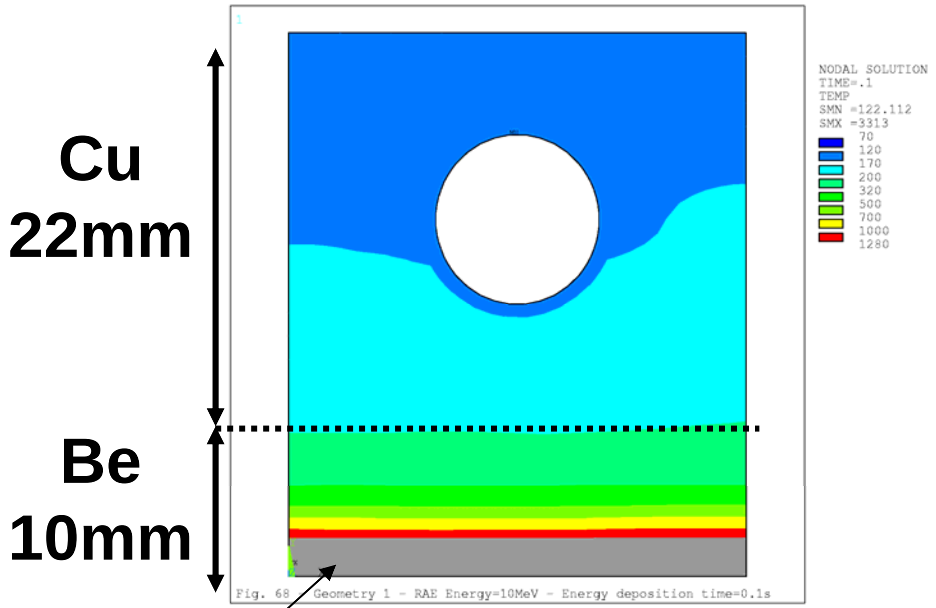
Without mitigation

Temperature pattern by RE flux,
RE energy = 10 MeV, angle = 1°
RE energy density = 50 MJ/m^2.
Deposition time = 0.1 sec.

$\Rightarrow$ **≈2.5 mm molten layer**



(Maddaluno)

Molten

Molten layer thickness strongly depends on wall design

For incident angle of 3°, ≈7.5 mm molten layer

Lifetime can be 1-4 times of RE events

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Summary of required R&D and examinations of design changes relating to injection / pumping / gas processing system

	Injector	Pumping/Gas process
(1) Massive gas injection (MGI)	Gas injector up to 500 kPa·m^3 from one injector*)	Helium (500 kPa·m^3) and Neon (100 kPa·m^3)
(2) Massive pellet injection (MPI)	Pellet injector Neon (40 kPa·m^3) Max 76 mmϕ*)	*Neon (40 kPam^3) (This can be covered by MGI case)*
(3) Massive Be injection	Beryllium injector (400 g) Max 75 mmϕ*)	*Not required*

***) Most demanding case with only one injection port assuming localized radiation load is acceptable**

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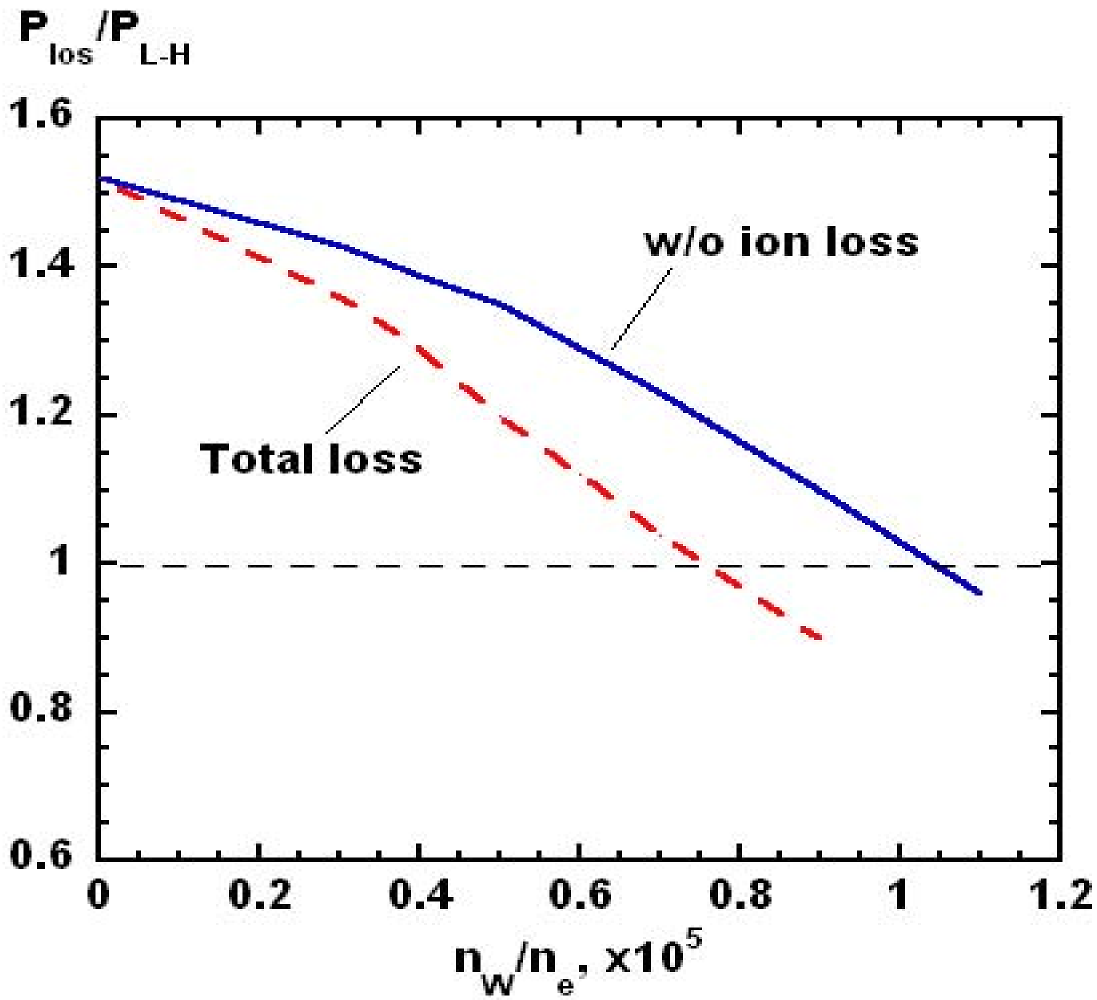
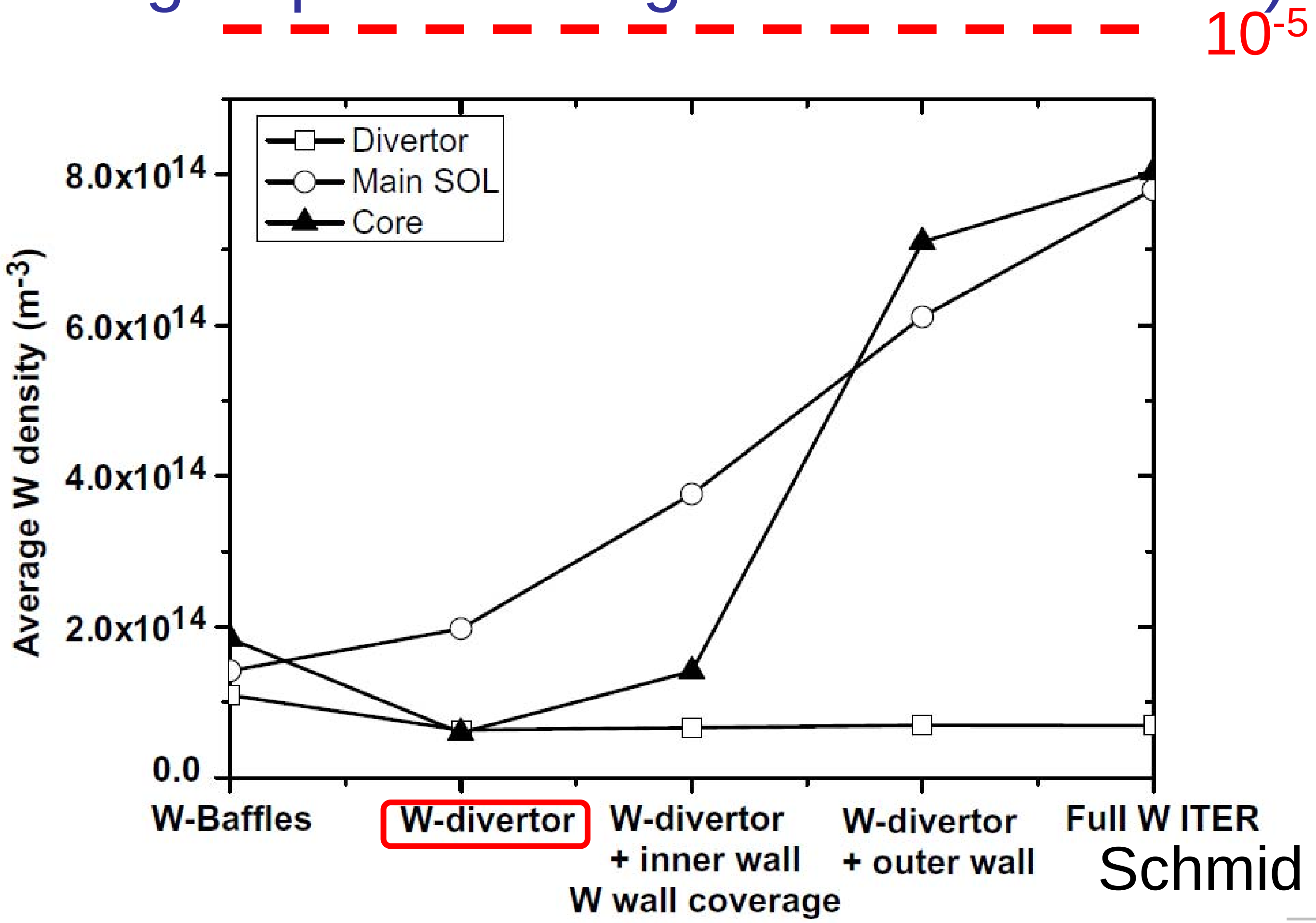
Acceptable level of tungsten in the core

In order to maintain H-mode, the power reaching the pedestal P_{los} is required to be (at least) L-H transition power P_{LH}. In addition to the electron-impact excitation, ionization and recombination loss(Post), ion-impact excitation needs to be included. The acceptable level of tungsten in the core is ~ 10^{-5} (Polevoi).



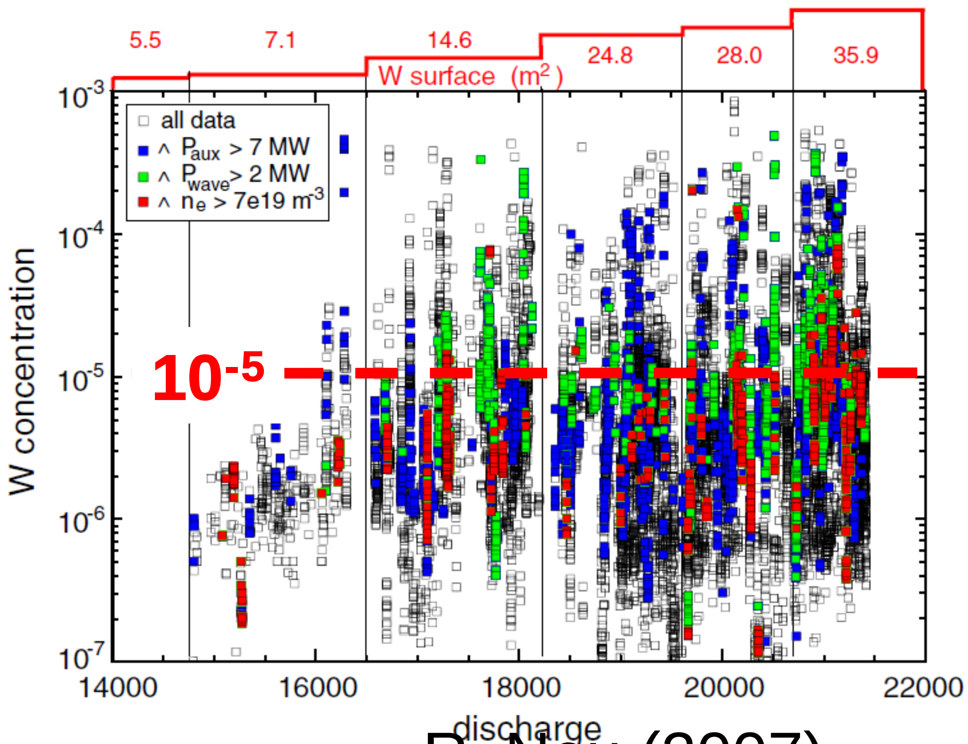
Polevoi 2008

Tungsten concentration is estimated to be ~10^{-6} in the core with W-divertor (no account of either ELM, edge melting or post-melting deformed surface)



Schmid 2007

AUG experiments show W levels higher than 10^{-5}, suggesting that adoption of high Z PFM would preclude some operation regimes (e.g. peaked densit, infrequent ELMs, low n_{sep})



R. Neu (2007)

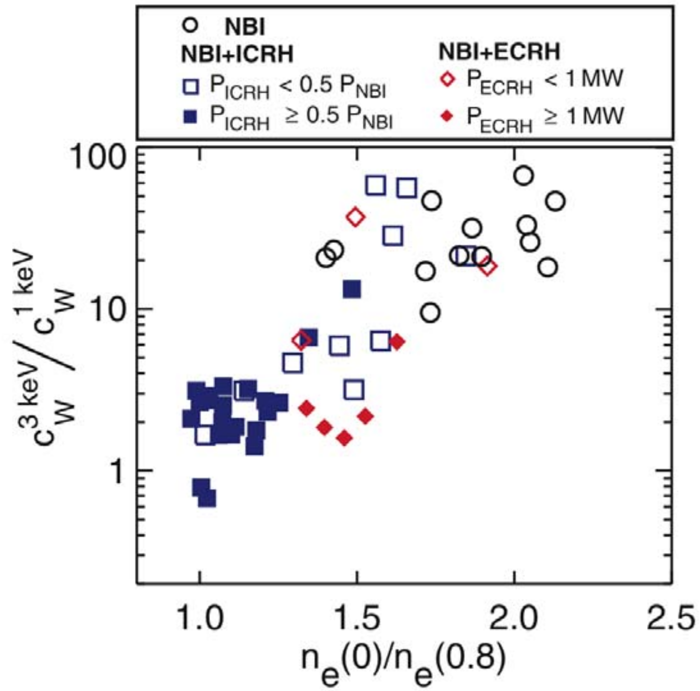


Figure 13. Peaking of the W concentration (c_W) as a function of background density. Discharges with pure NBI heating (black circles) show the strongest peaking, whereas central ECRH reduces the c_W peaking significantly already at low additional heating power.

Tritium inventory

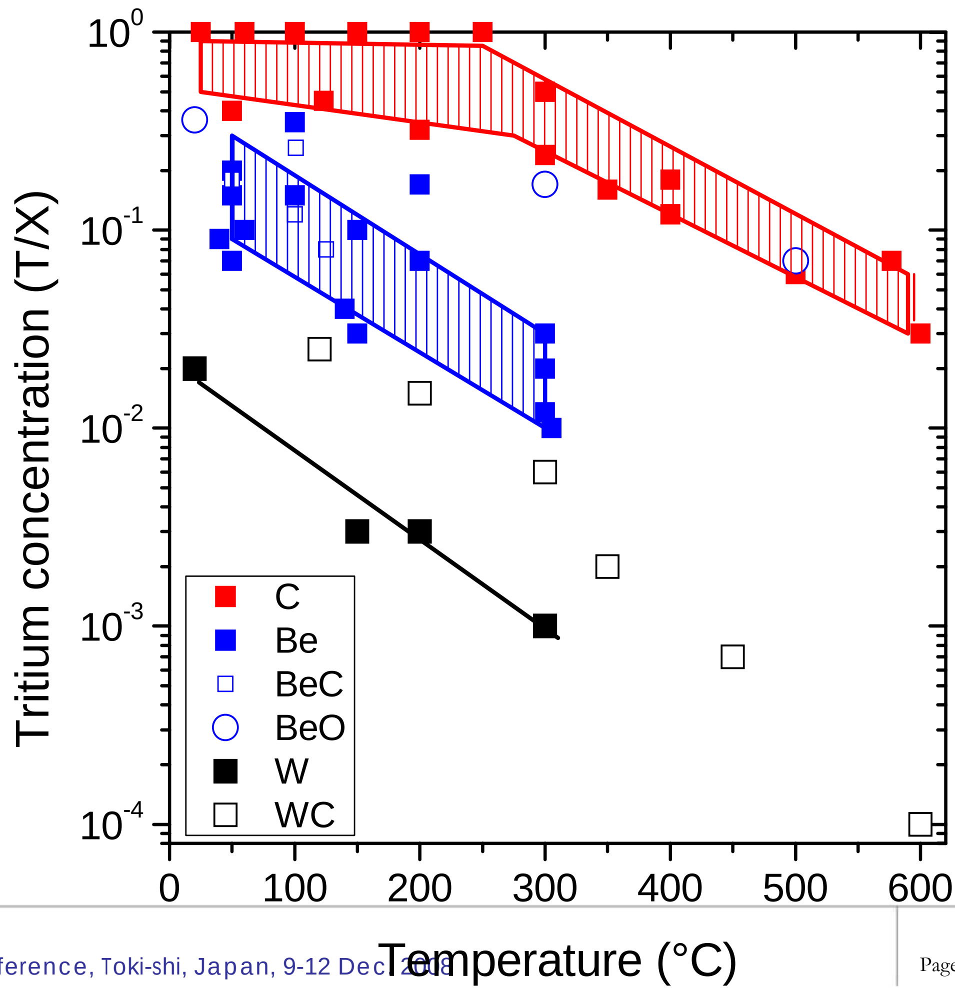
G. De Temmerman
J. Roth

Erosion determines co-deposition:

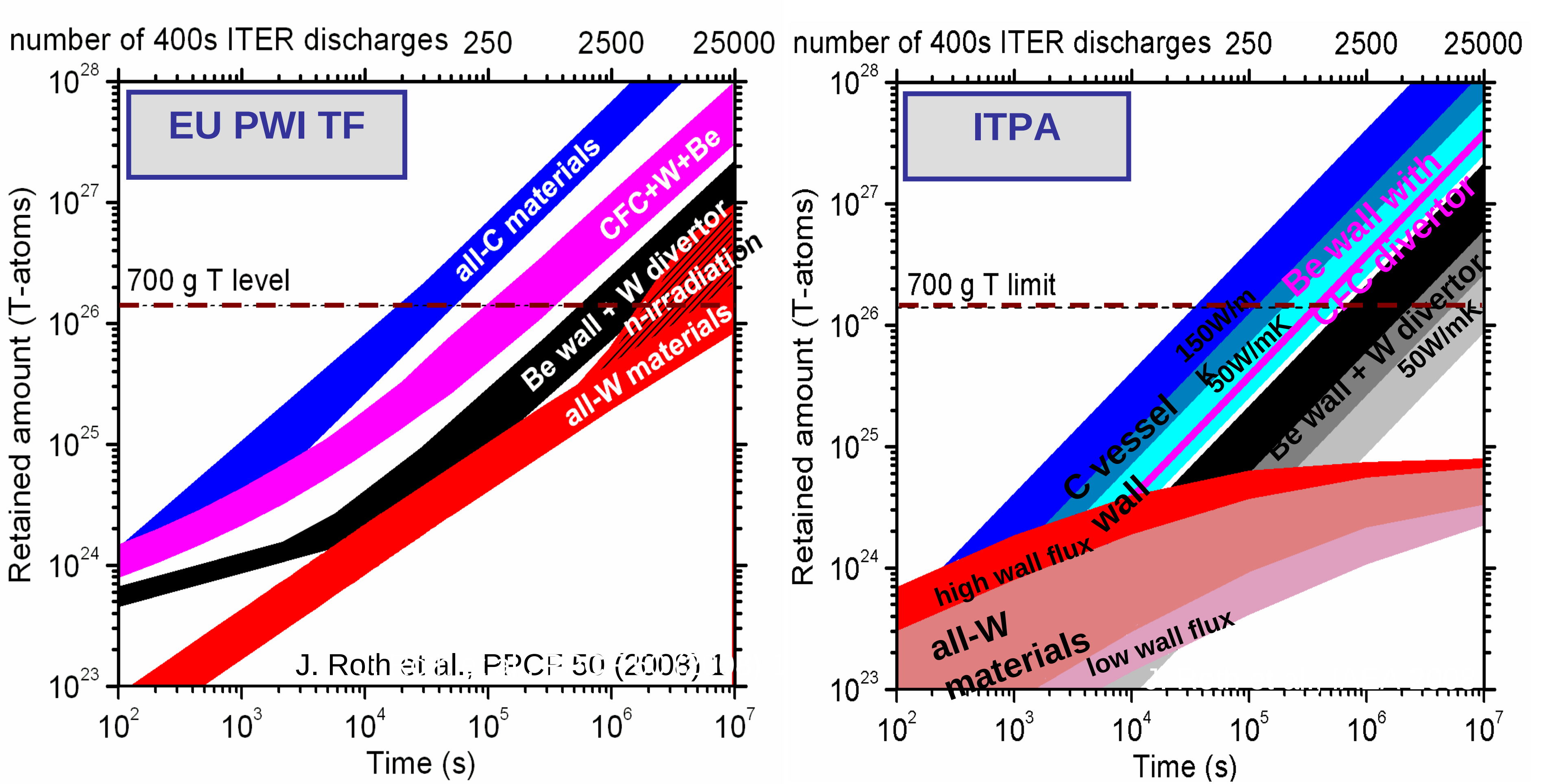
- ❑ Rough estimate: total net erosion rate x co-deposition concentration
- ❑ Detailed evaluation: impurity transport including re-erosion, co-deposition concentration depending on final deposition conditions

Co-deposition with C and Be depends on deposition conditions: energy, deposition rate, temperature

	atoms/s	g/shot
Be wall	$3x10^{20}$	1.8
CFC divertor	$2x10^{21}$	3.2
W divertor	$4x10^{17}$	$8x10^{-4}$



T-inventory build-up estimates

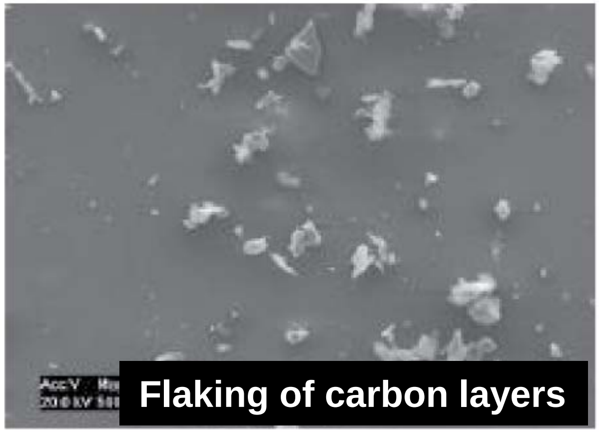


Reasonable agreement between the two approaches

- With Be wall + CFC divertor → ~few 100 discharges before limit is reached
- Might be allowed ~>2500 full power pulses with Be wall + W divertor

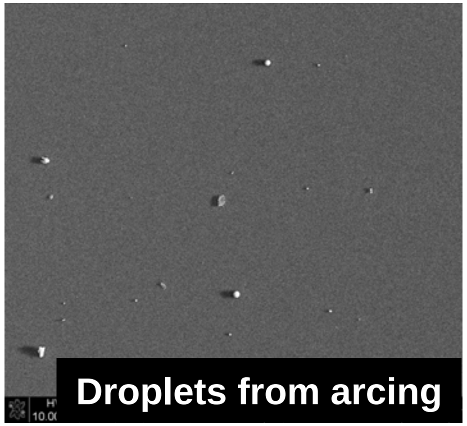
Dust generation

Collection July 2000



Flaking of carbon layers

Collector probes 2007



Droplets from arcing

AUG

full-C and full-W phase

J. Sharpe, V. Rohde et al., JNM 2003

M. Balden et al, PSI-2008

Potential safety concerns:

Hydrogen production when hot dust reacts with steam

Be major contributor — **Hot dust limit**

with carbon: ⇨ **6 kg C, 6 Be, 6 kg W limit**

without carbon: ⇨ **11 kg Be, 76 kg W limit**

Possible pure Dust or Hydrogen/Dust explosion

Be, C, W involved

Potential release in environment ⇨ **1000 kg limit in VV**

W dust can be radioactive

Dust may contain Tritium

Roth 2008

Dust generation

Total dust generation:

Assumption:

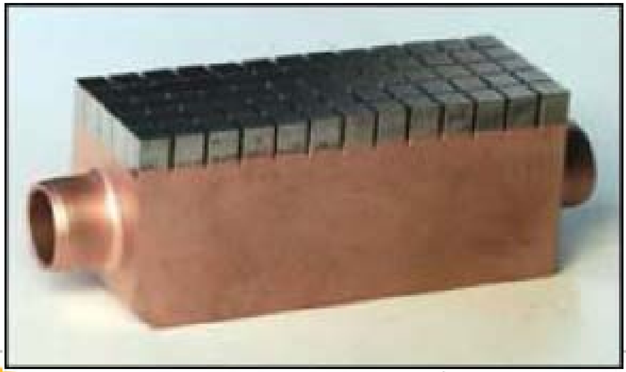
- ❑ Dust generation dominated by erosion, deposition, layer disintegration
- ❑ Conversion from erosion to dust for safety reasons: 100 %
  (about 10 % in Tore Supra and JT-60U)

Total dust limit not reached before scheduled maintenance and exchange of divertor cassettes (J. Roth PSI-2008)

Dust on hot areas: (A. Litnowski PSI-2008)

Assumption:

- ❑ On hot plasma wetted areas, dust will only survive in castellation



Assume dust at hot area collects only in gaps:

Flux of Be to outer target hot zone (DIVIMP): $2\times10^{19}/m^2s$

Area of hot zone: $8m^2$

⇨Total Be flux: $1.6\times10^{20}/s \approx$ 1g/discharge

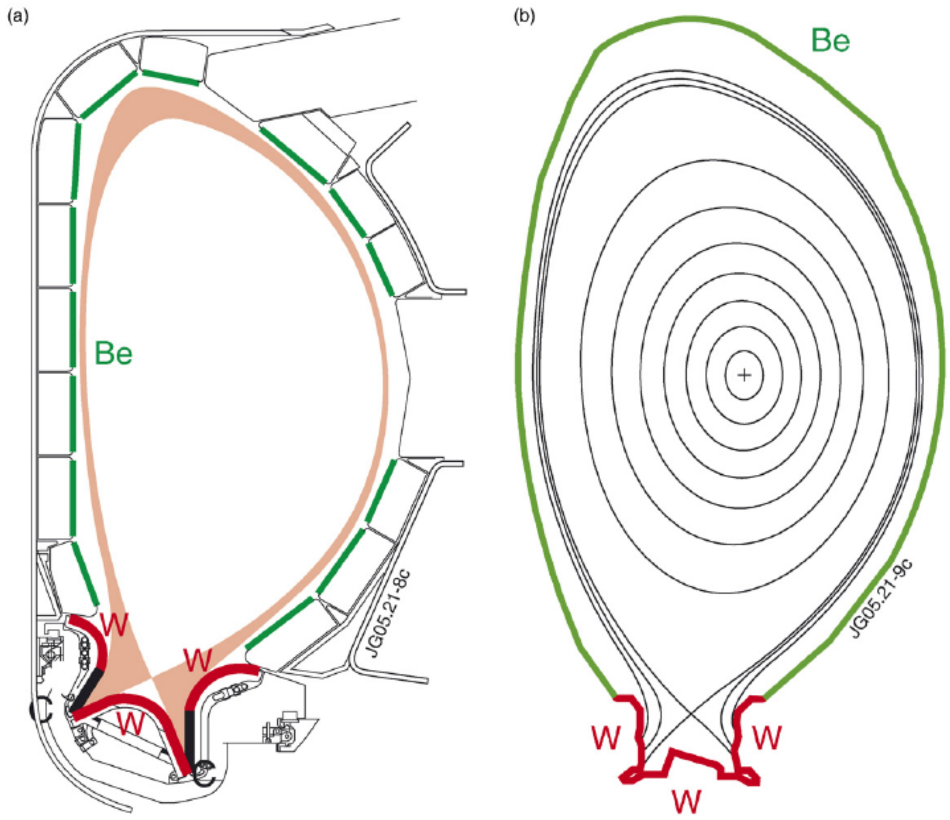
Gap area 2%

⇨Hot Be dust rate: 0.02g/discharge

⇨ **11kg Be dust for W/Be wall in 60000 disch.**

Roth 2008

A strong collaboration programme

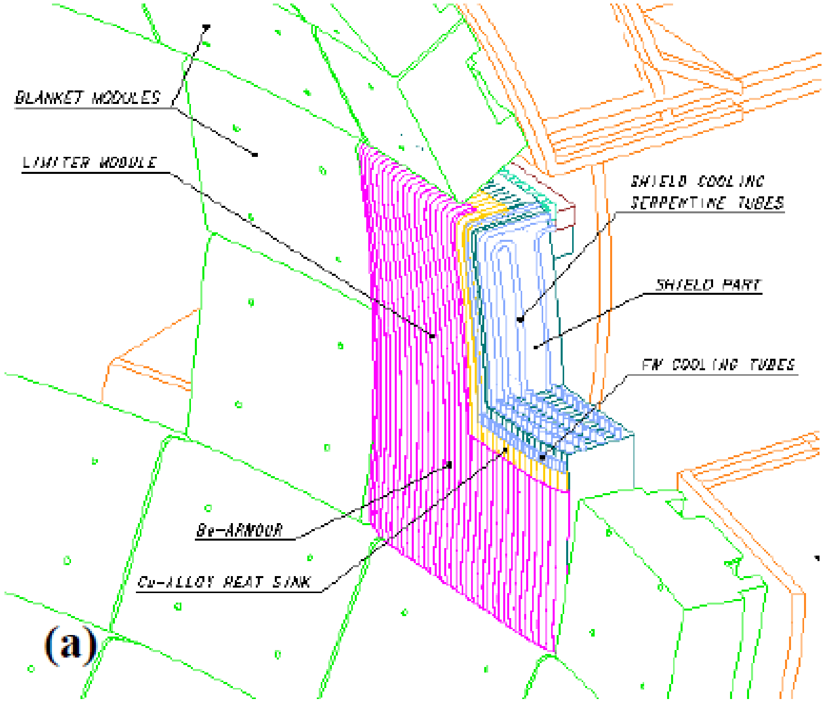


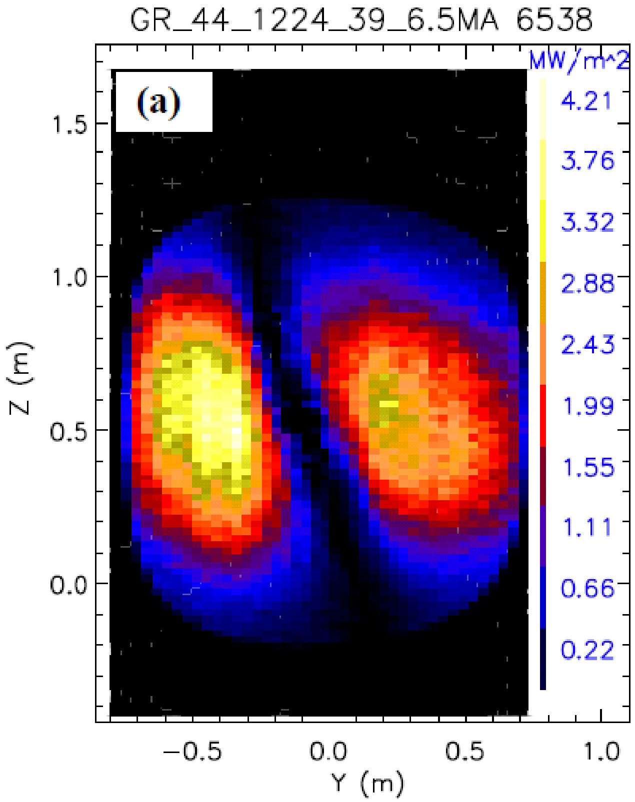
- JET will carry out ITER-Like-Wall experiments from 2010 (Be wall and full tungsten divertor)
- ASDEX-Upgrade and C-mod will continue experiments with high Z PFCs
- ITPA, EU PWI TF, USBPO will execute experiments focused on tritium retention, dust, erosion, heat loads on PFCs, ELM mitigation, disruption mitigation, wall conditioning…., emphasizing cross-machine comparision

Summary

- The thermal load specification on PFCs has been updated, confirming serious consequences of transient loads, e.g. ELMs, disruption
- The mitigation measures of ELMs and disruption are under development
- Current estimates suggest that tritium retention will reach ~ 700 g after a few hundred DT shots of 400s burn with CFC-W-Be PFCs, a few thousands DT shots with full tungsten divertor and Be FW
- The operation range with full tungsten divertor appears to be limited
- Baseline plan is to change the divertor cassettes to full W before DT operation, but limited use of CFC target during DT is not ruled out
- A strong collaboration programme is developed and carried out under the framework of ITPA, EU PWI TF, USBPO to address ITER PWI issues

Examples of successful collaboration





3d calculation of sol and limiter heat load (Kobayashi)
Pipe-gun type pellet injector (Sakamoto)